Development of an Operational Multi-sensor and Multi-channel Aerosol Assimilation Package Using NAAPS and NAVDAS

Jianglong Zhang
Department of Atmospheric Sciences
University of North Dakota
phone: (701) 777-6342 fax: (701) 777-5032 email: jzhang@atmos.und.edu

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LONG-TERM GOALS

Due to the significance of aerosols in visibility forecasting, transportation, air pollution and global climate change studies, the modeling and successful prediction of aerosol events is of a great interest to both military and civilian users. Recognizing this interest, the Naval Research Laboratory Marine Meteorology Division developed the Navy Aerosol Analysis and Prediction System (NAAPS), the world's only truly operational aerosol prediction model, to provide both aerosol and visibility forecasts for the US Navy.

A recent study showed that by ingesting over ocean satellite observations into NAAPS through a data assimilation process, the NAAPS' forecasting capability could be improved by 20-40%. This research effort, however, also found that there are remaining fundamental issues that must be addressed before a global (i.e., ocean and land) aerosol data assimilation can realistically be ported to operational use. These include:

(1) Need to develop an over-land (with bright surface areas) aerosol data assimilation capability;

(2) Need to improve observational data coverage through a multi-sensor data fusion/data assimilation technique;

(3) Need to utilize multi-channel information to improve accuracies in NAAPS aerosol vertical profile and speciation;

(4) Need to develop a better parameterization for characterizing model forecasting errors.

We are investigating these issues and are developing a multi-sensor and multi-channel aerosol assimilation package using level 2 aerosol products from the Moderate Resolution Imaging Spectroradiometer (MODIS) collection 5, MODIS Deep Blue, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), and Advanced Along Track Scanning Radiometer (AATSR). We will also integrate geostationary, polar orbiter and even surface network data once they become available. This research is destined for operational use at the Fleet Numerical Meteorological and Oceanographic Center (FNMOC), and will greatly advance air quality, visibility and climate programs that by necessity are turning to aerosol data assimilation techniques.

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14. ABSTRACT
Due to the significance of aerosols in visibility forecasting, transportation, air pollution and global climate change studies, the modeling and successful prediction of aerosol events is of a great interest to both military and civilian users. Recognizing this interest, the Naval Research Laboratory Marine Meteorology Division developed the Navy Aerosol Analysis and Prediction System (NAAPS), the world?s only truly operational aerosol prediction model, to provide both aerosol and visibility forecasts for the US Navy.

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APPROACH

The goal of this study is to improve the Navy's electro-optical propagation forecast capability through a multi-channel and multi-sensor aerosol data assimilation method. In contrast to data assimilation schemes for traditional atmospheric variables, large uncertainties exist in the satellite aerosol products. Therefore, for the first step, quality assurance and empirical correction procedures are required before incorporating such aerosol products into numerical forecasting models. This step involves extensive studies of the uncertainties in satellite aerosol optical properties as functions of observational conditions (such as clouds, surface conditions, and aerosol properties), through the combined use of ground-based observations, cross-sensor inter-comparisons, and satellite and modeling aerosol optical property comparisons. The quality assurance steps will be applied once a new sensor is included in the assimilation process (such as MODIS, MISR, and MODIS DeepBlue), and will be updated when a newer version of an aerosol product from a sensor is released (such as the updating of MODIS aerosol products from collection 4 to 5).

As the second step, the data-assimilation-quality aerosol products will be included into the data aerosol assimilation process. Currently, using the univariate two-dimensional capabilities of the NRL Atmospheric Variation Data Assimilation System (NAVDAS), an aerosol assimilation package NAVDAS-AOD has been developed for assimilating satellite aerosol optical depth data into NAAPS. NAVDAS-AOD is currently transitioned to FNMOC for operational use with the inclusion of data-assimilation quality over water MODIS aerosol product. New quality assured aerosol products (such as MISR and MODIS DeepBlue aerosol products) will be incorporated into the analysis once available. New aerosol assimilation functionalities including assimilating multi-channel information for aerosol speciation, and 3-D aerosol assimilation capability will be developed.

Finally, the new aerosol assimilation functionalities and the new aerosol products will be evaluated for their impacts on aerosol prediction and forecasts, and components that have a positive impact on the operational aerosol forecasts will be transition to NRL for further implementation in FNMOC.

WORK COMPLETED

The accurate knowledge of aerosol vertical distribution is critical to the aerosol forecasting capability. Last year, a CALIPSO climatology was implemented in the NAVDAS-AOD. However, aerosol vertical distributions also have a very high temporal dependence and may not be well represented by climatologies that are averaged through a long period of time. In realizing this limitation, and in collaboration with Dr. Reid from NRL and Dr. Campbell from UCAR/NRL, we developed a prototype for directly assimilating 3-D aerosol vertical profiles from CALIPSO. Although the new 3-D CALIPSO aerosol assimilation package is still undergoing the evaluation and validation stages, the initial results from the 3-D CALIPSO aerosol data assimilation are very promising (Figure 1).

Currently, the NAVDAS-AOD is transitioned to FNMOC through the use of the operational MODIS over ocean aerosol product. A new version of the MODIS aerosol product, the collection 5, has been recently released by the MODIS aerosol team. Extending from last year's research efforts, using a total of nine years of Terra MODIS (2000-2008) and seven years of Aqua MODIS (2002-2008), we developed quality assurance and empirical correction procedures for generating data-assimilation-friendly over water MODIS aerosol products. The results of this study have been documented in graduate student Yingxi Shi's M.S. thesis. A manuscript for a journal paper is also in preparation. The

new algorithm was sent to NRL Monterey for inclusion in the latest version of NAVDAS-AOD. This research activity is a joint research effort from this project, and the no-cost of extension of the project N00014-08-1-0264.

Using nine years (2000-2008) of collocated MISR and AERONET data, we evaluated the performance of MISR aerosol products over both land and ocean. We are currently working on developing data assimilation quality MISR aerosol products, and will document our findings through a peer-reviewed paper.

Following from last year's research efforts, we finalized our study on the analysis of clear sky and other cloud-related contextual biases existing in satellite aerosol products. This study has been published in GRL this year. The work here is built upon the extension of the project N00014-08-1-0264.

Understanding of the long term variation of aerosol optical properties is important for climate related studies, and is extremely valuable to studies that trying to evaluate the aerosol induced thermal perturbations to regional and larger scale atmospheric circulations. Using the quality assured aerosol product from MODIS, we studied the long term trend of aerosol optical properties. A manuscript is in preparation.

RESULTS

Three dimensional aerosol assimilation using CALIPSO: using NAVDAS-3D, a prototype for the CALIPSO aerosol data assimilation has been developed through the collaborative efforts from the Dr. Reid (NRL) and Dr. Campbell (UCAR/NRL). At the first step, a data-assimilation-friendly CALIPSO aerosol product has been created. A prototype of a three-D CALIPSO data assimilation scheme has been further developed to incorporate the 3-D CALIPSO data into the aerosol prediction and forecasting cycles. For example, Fig. 1a depicts the Level 1B CALIPSO backscatter product for the 1533 UTC orbital pass on 20 July 2007. An elevated dust plume is visible from 1.0 to 5.0 km, with smoke present near the surface. The identification of these layers is aided by the linear depolarization ratio data showing in Fig. 1e. Dust, with highly irregular shapes, readily depolarizes laser energies. Fresh smoke, which is typically deliquesced, does not depolarize since backscatter from spherical particles is dominated by the reflection of the rear face. Fig. 1d depicts the assimilation-ready CALIPSO extinction profile [*Campbell et al.*, 2009] after QA, QC, cloud clearing, and spatial averaging. In Fig. 1c, vertical profiles of aerosol extinction from a NAAPS run with MODIS assimilation shows how the model is able to resolve the major aerosol feature present. The model, however, fails to resolve low-level structure and other aerosols seen with the lidar. In Fig. 1e, the NAAPS analysis after 3-D variational CALIPSO data assimilation shows how the model analysis is radically improved. Aside from the dust feature, all of the other major aerosol features are resolved vertically.

Nine-years Terra and seven-years Aqua MODIS analysis for constructing data assimilation quality MODIS aerosol products: using nine years of TERRA and seven years of AQUA data, the over-water aerosol optical depth (AOD) from the Moderate Resolution Imaging Spectroradiometer (MODIS, Collection 5) aerosol products was evaluated for its potential usage in aerosol data assimilation. Uncertainties in the over-water MODIS AOD were examined as functions of observing conditions, such as surface characteristics, aerosol optical properties, and cloud artifacts. Empirical corrections

and quality assurance procedures were developed. After applying quality assurance and empirical correction procedures, the uncertainties in the MODIS TERRA and AQUA AOD are reduced by 20% and 12%, respectively. Nine years of TERRA and seven years of AQUA quality-assured level 3 MODIS over-water aerosol products were produced. The newly developed MODIS over-water aerosol products will be used in future aerosol data assimilation and aerosol climatology studies, and will also be useful to other researchers who are using the MODIS satellite products in their projects.

An analysis of clear sky and contextual biases (abstract from the paper Zhang and Reid, 2009): clear sky and other cloud-related contextual biases are critical yet unsolved mysteries for aerosol related climatological studies using satellite observations. For the first time, we simulated contextual biases over ocean using 2-years of Navy Aerosol Analysis and Prediction System (NAAPS) products that include the Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth (AOD) assimilation. We compared model-derived AOD in regions with and without observations, and found that sampling results in negligible seasonal globally averaged AOD bias (< 5%). Biases are more pronounced in regions with frequent overcast skies and high aerosol loadings, such as Southeast Asia, and mid-latitude South America. This suggests that contextual biases may develop from transport covariance and other observing biases. Lastly, we found that over remote oceans, under cloud decks, a slight increase aerosol optical depth values could exist, compared with cloud free regions. But this is still small relative to cloud artifacts in the retrieval.

Evaluation of the MISR aerosol products: nine years of MISR aerosol products (2000-2008) over both land and ocean were evaluated against the ground-based AERONET observations. Our study suggested that the over ocean MISR aerosol product meets the reported accuracy, and especially, the over land MISR aerosol product proved to be more robust than that of MODIS, and can be used for future inter-comparisons with MODIS aerosol products over land. However, our study also suggested that cloud contamination, and especially cirrus cloud contamination, is still a problem for the MISR aerosol product. Therefore, quality assurance and quality check procedures are necessary before we implement MISR into the data assimilation cycles, and /or use it for cross-sensor inter-comparisons.

Long-term trend analysis: Using nine years of over water Terra and Aqua MODIS aerosol products, we studied the regional and global aerosol optical depth trend over oceans. Our study suggests that a negligible trend in aerosol optical depth (AOD) was found using the over water Terra MODIS aerosol data over global oceans, after correcting for sensor's calibration shift. This finding is contradictory to a much larger decreasing trend as reported by *Mishchenko et al.*, [2007] using the AVHRR data. Regionally, our study showed that large increases in AOD are found over the coastal India, Arabian Sea, and southeast coast of Africa regions for the past nine years. Especially over the coastal India region, the increase in AOD indicates a worsening scenario to the already heavily polluted air, and could have a strong impact to local regional climate.

IMPACT/APPLICATIONS

The Observing System Simulation Experiment (OSSE) suggests that the absolute error in NAAPS 24-48 hour aerosol forecasts can be reduced by as much as 40%, using aerosol data assimilation with the over water MODIS aerosol product. Similar results are found for the over land aerosol data assimilation from a research effort lead by Dr. Reid and Dr. Hyer from NRL. We expect further increases in performance with the inclusion of MISR, and MODIS DeepBlue aerosol products.

TRANSITIONS

The algorithm for constructing a data assimilation quality MODIS collection 5 over water product has been delivered to NRL Monterey for future implementation to FNMOC.

The NVA (NAVDAS-NAAPS-AERONET), a system that is designed for testing and evaluation of the aerosol assimilation system, has been delivered to NRL Monterey.

RELATED PROJECTS

This project is tightly coupled to a number of ONR 322 programs at the Marine Meteorology Division Aerosol and Radiation Section on the further development of the Navy's aerosol forecasting capabilities. This includes an integrated effort with the Earth Sciences Applications project of JS Reid on the development of NAVDAS-AOD, the model integration with the Large Scale Aerosol Modeling Development project of D. L. Westphal, and a no-cost extension of an one-year project (N00014-08-1-0264) of Dr. Jianglong Zhang. Lastly, we are beginning enhancements to 3-D and 4-D variational analysis in cooperation with the NRL data assimilation section (Bill Campbell and Nancy Baker).

PUBLICATIONS

Zhang, J. and J. S. Reid, An analysis of clear sky and contextual biases using an operational over ocean MODIS aerosol product, *Geophysical Research Letters*, 36, L15824, doi:10.1029/2009GL038723, 2009 [published, refereed]..

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HONORS/AWARDS/PRIZES

Jianglong Zhang, University of North Dakota, Presidential Early Career Award for Scientists and Engineers.

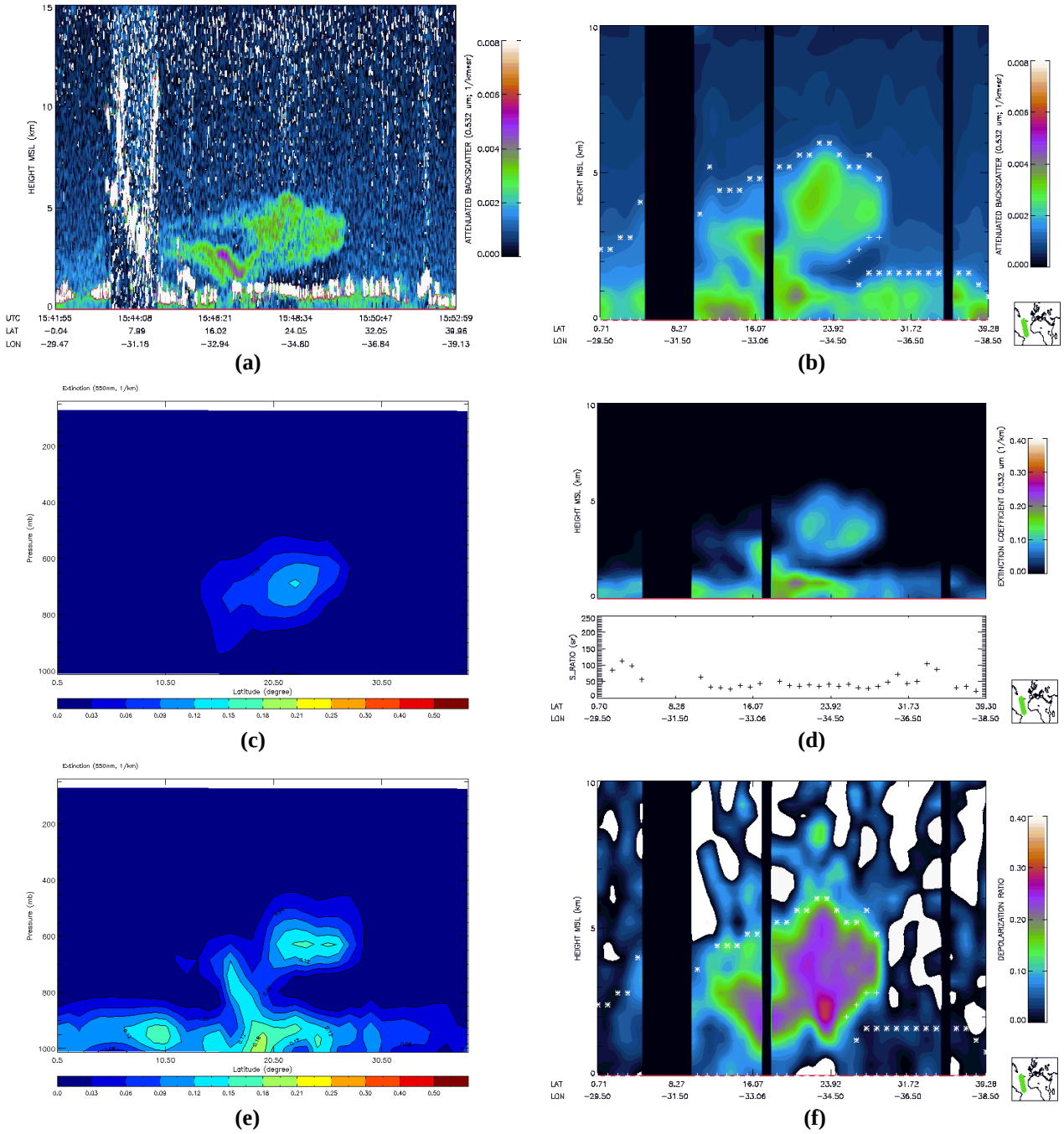

Figure 1. (a) CALIOP 0.532 µm attenuated backscatter (km^{-1} sr^{-1}) for 1522 UTC orbital pass 20 July 2007, 0º to 40º N from 0.0 to 15.0 km MSL; (b) 1º along-track gridded attenuated backscatter profiles from 0.0 to 10.0 km MSL; (c) NAAPS analysis of extinction coefficient (km^{-1}) from 1000.0 to 100.0 hPa for this pass using only MODIS/MISR optical depth assimilation; (d) 0.532 µm extinction coefficient and extinction-to-backscatter ratios for inversion constrained by NAAPS optical depths in (c); (e) NAAPS extinction coefficient (km^{-1}) post-CALIOP assimilation; (f) 0.532 µm CALIOP 1º along-track linear depolarization ratio. Derived aerosol layer boundaries are denoted by asterisks (top) and plus symbols (bottom), respectively.